

# INL Electrochemical Performance Testing

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# Overview

## Timeline

- Established in 1985
- Activity On-going

## Budget

- FY 2014: \$3.0M (AES)
- FY 2015: \$3.0M (AES)

## Barriers

- Testing and analysis strategies are critical to accurately characterizing the **performance** (energy density), **life** (5,000 – 300,000 cycles; application dependent), **reliability** (high temperature) and **cost** (~ \$300/kWh) of advanced energy storage devices for vehicles.

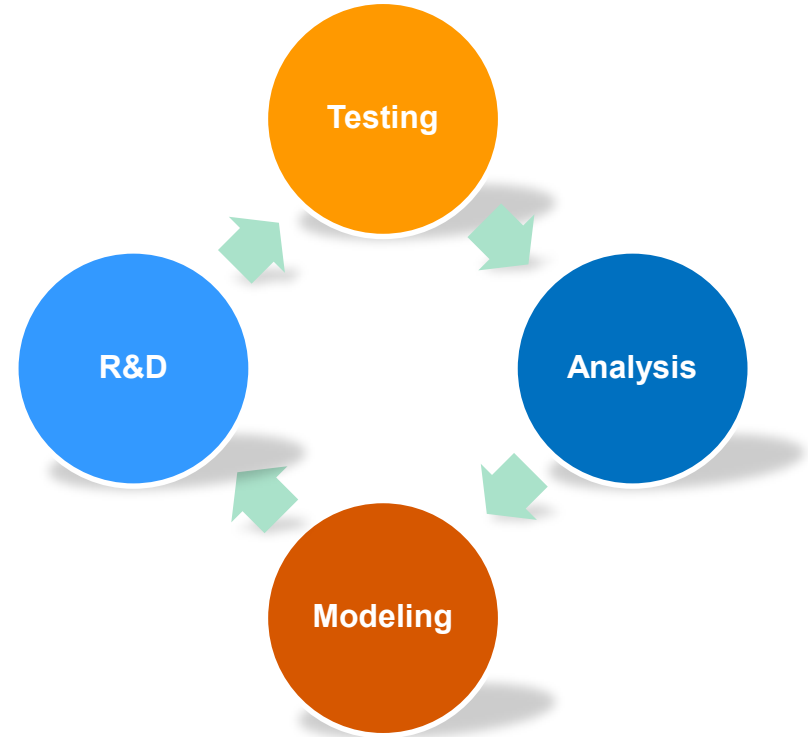
## Partners

- **USABC** – Energy Storage Technical Advisory Committee
- **Argonne National Laboratory**
  - Testing, Analysis, Life Prediction Tools
- **Sandia National Laboratories**
  - Abuse Tolerance, Life Validation Methods
- **National Renewable Energy Laboratory**
  - Thermal Imaging, Analysis, Models
- **Others**
  - AVTA, DOT (NHTSA), Private Industry



## *Technical Challenge*

- Advanced battery chemistries intended for vehicles are being introduced to the automotive industry at an accelerated rate
  - DOE supported battery research is a major reason for this positive trend
  - Transitioning chemistries from the lab to the consumer often fails due to inadequate testing early in the R&D cycle

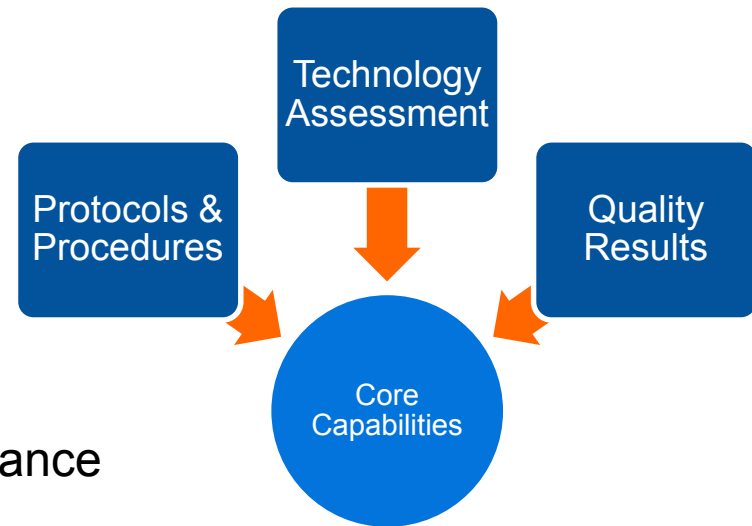


***Quality testing/validation/analysis is critical for adoption/success in the market***

## Objective

*Independent, science-based performance assessment of energy storage devices.*

- Environmental control
- Software analysis tools for data analysis and reporting.
- Standards developed for data acquisition, analysis, quality, and management.
- **Protocols & Procedures**
  - Internationally accepted manuals for performance assessment of energy storage systems.
  - **Lead National Laboratory** for technical content and authorship with support from DOE and USABC.
- **Quality Results**
  - Flexible state-of-the-art energy storage test facility capable of supporting current and future development activities.
  - Rigorous NIST traceable calibration procedures for in depth uncertainty analysis
  - Temperature controlled testing for reliable and repeatable results.



# Milestones

Year	Program	Description	Status
2014	USABC / DOE	Deliverables testing 1Q quarterly report	Complete
2014	USABC / DOE	Deliverables testing 2Q quarterly report	Complete
2014	USABC / DOE	Deliverables testing 3Q quarterly report	Complete
2014	USABC / DOE	Deliverables testing 4Q quarterly report	Complete
2014	USABC / DOE	PHEV Manual Revision 3	Complete
2014	USABC / DOE	EV Manual Revision 3	Delayed*; Expected Completion 6/2015

\* Major overhaul of the PHEV (Rev 3) test manual consumed more time than all involved parties initially anticipated. This PHEV manual cast the foundation for testing and analysis methodology that will serve as the basis for all future test manuals, EV included. **Extension of EV Test Manual Revision 3 was approved by VTO program manager.**



# Milestones

Year	Program	Description	Status
2015	USABC / DOE	Deliverables testing 1Q quarterly report	Complete
2015	USABC / DOE	Deliverables testing 2Q quarterly report	Complete
2015	USABC / DOE	Deliverables testing 3Q quarterly report	On Schedule
2015	USABC / DOE	Deliverables testing 4Q quarterly report	On Schedule
2015	USABC / DOE	Technology trending (progress and performance) for developer test articles; Report results to USABC and DOE	On Schedule
2015	USABC / DOE	Conduct feasibility study on low-temperature assessment of rapid impedance measurements; Report to USABC and DOE	On Schedule
2015	USABC / DOE	Host a Tech-to-Market (T2M) workshop for industry providing tutorials and demonstrations of Electric Drive Vehicle battery performance, testing protocols, and data analysis.	On Schedule

# Approach

- **INL Battery Test Center (BTC)**

- Cell, Module, and Pack Performance Assessment
- Testing and Analysis Procedures
- Data Quality Standards



- **Advanced Vehicle Testing Activity (AVTA)**

- Electric Vehicle Infrastructure Deployment Testing and Analysis
- Alternative Fuel Transportation Systems Testing and Analysis



***INL Role: Quality Testing and Applied Research***

# Technical Accomplishments/Progress

- **World Class Facilities:**
  - Diverse selection of test equipment allows the Battery Test Center (BTC) to assess the performance of many different deliverable configurations for cell to module to full vehicle packs.
- **Data Quality and Procedures:**
  - Rigorous calibration procedures improve data quality
  - Standard lab operating procedures reduce setup variability
  - Active members of USABC TAC and workgroups
- **Results:**
  - Results reported to USABC, DOE and Manufacturers
  - The INL Battery Test Center (BTC) evaluated 535 cells, 23 modules, and 3 packs for a total of 561 articles in FY-2014
- **Performance Science:**
  - Understanding system performance based upon the intended environment, application, chemistry.



# Technical Accomplishments/Progress

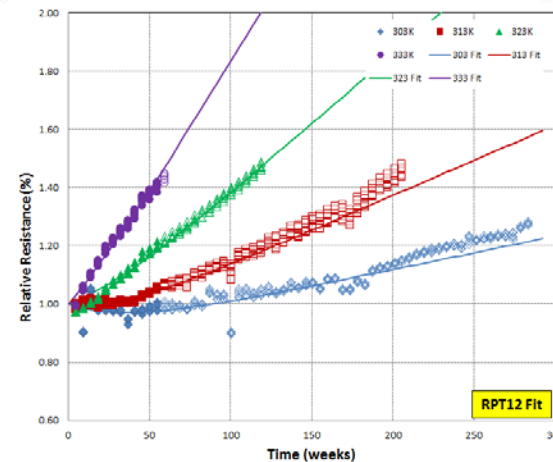
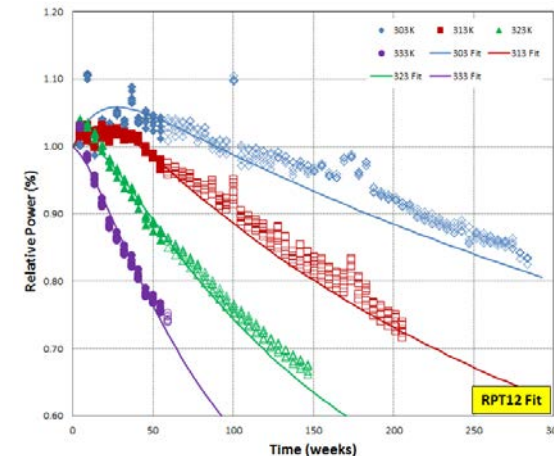
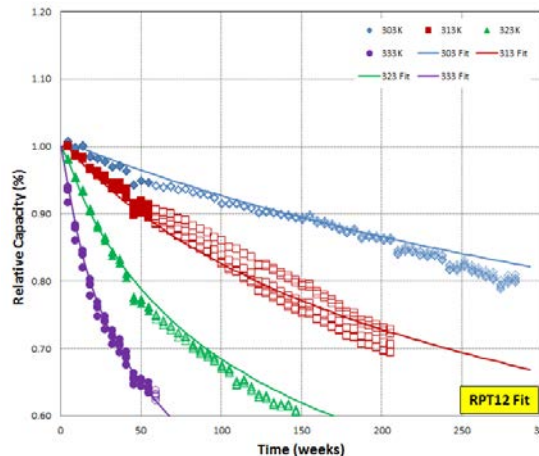
- INL Battery Test Center (BTC)
  - 705 cell test channels
  - 27 module test channels
  - 7 pack test channels
  - >100 controllable thermal chambers
  - Vibration test system



***Battery Test Center named DOE Core Capability for Electrochemical Performance Testing***

## Life Modeling: How Much Data?

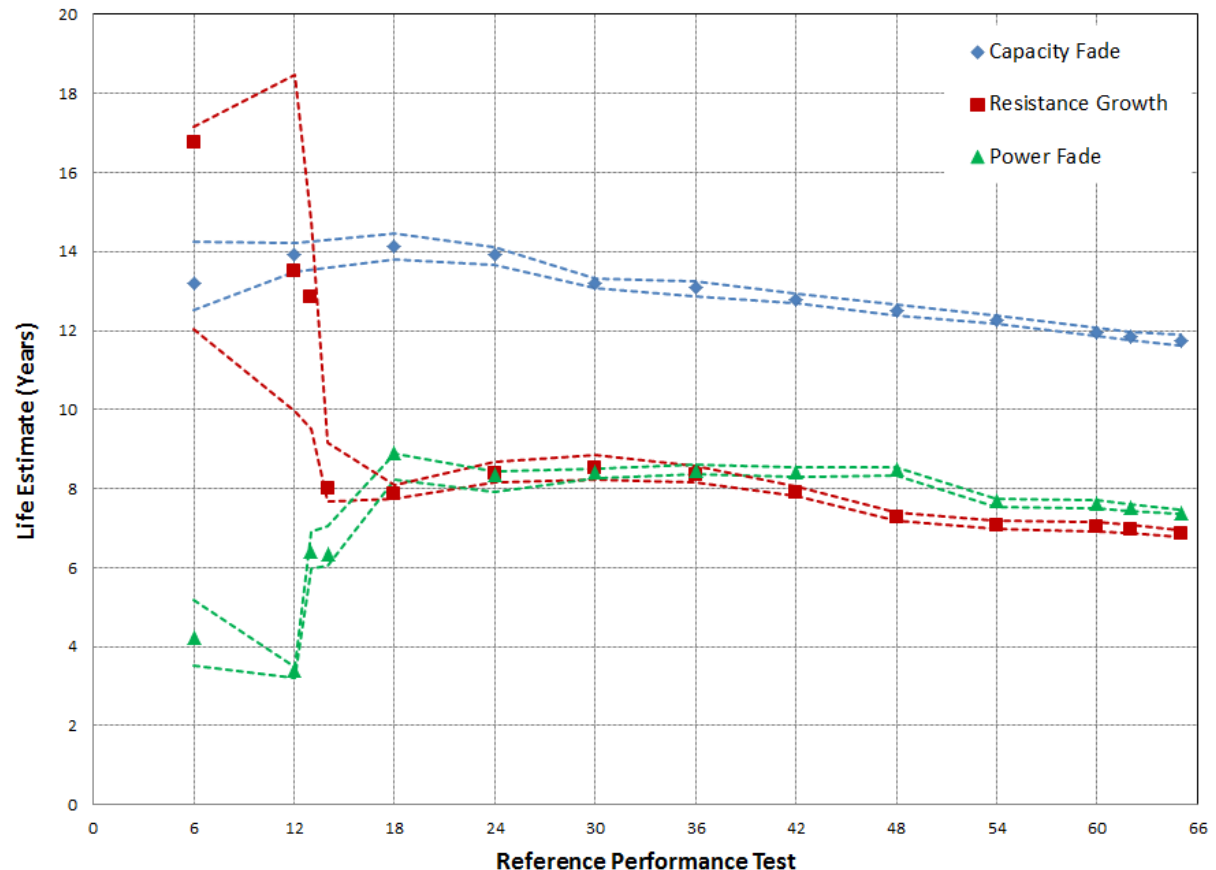
- Cell Specifications:
  - NMC/Graphite Pouch
- Model\*:
  - Battery Life Estimation and Data Analysis (BLE)
- Parameters Modeled:
  - Capacity, Power, Resistance
- Data:
  - Open Symbols not modeled



***The change in degradation parameter is limited by the lack of reactive materials for non linear model forms.***

## *Life Modeling: How Much Data? (cont.)*

- **Data:**
  - Resistance and Power are the dominant aging parameters in this case.
- **Life:**
  - Approximately 8 year life expected for this chemistry.

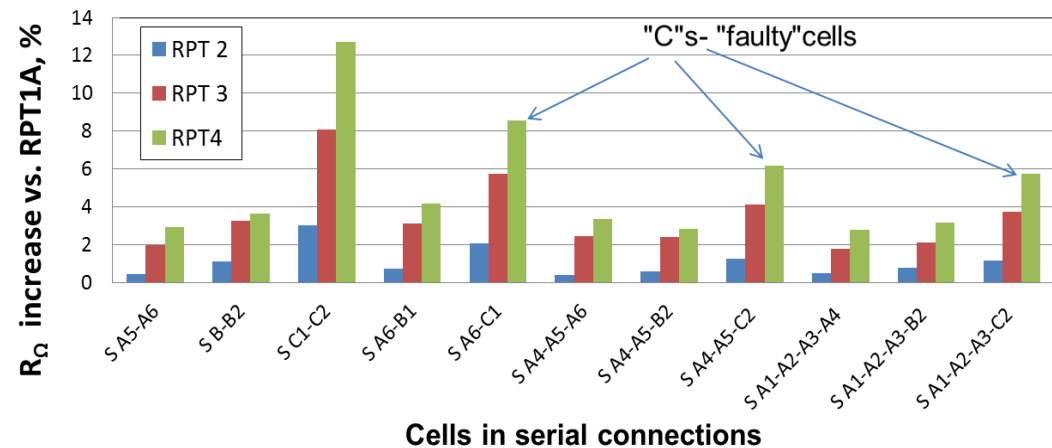
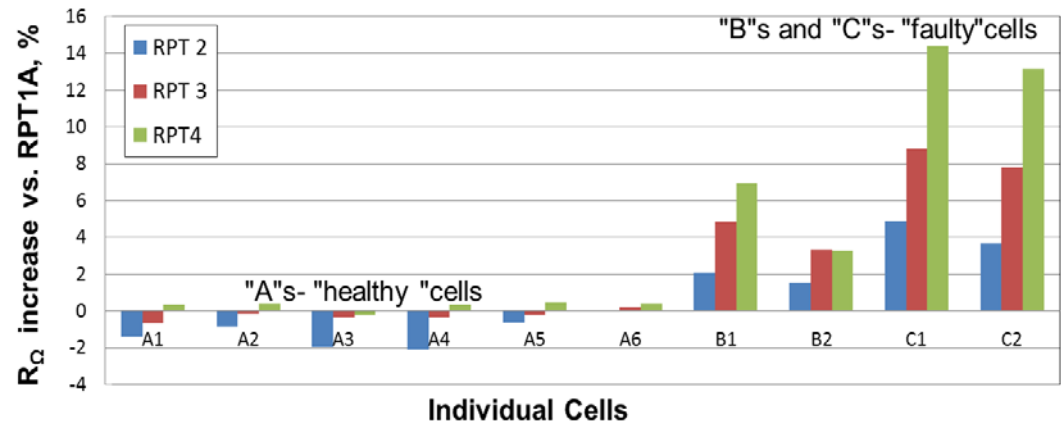


***For this chemistry, ~12 mo. of test data are required for the model (BLE) to consistently predict End of Life conditions.***

## String & Parallel Rapid Impedance

- **Goal:**
  - Assess the capability of rapid impedance measurement technique (IMB) to detect faulty cells in different architectures of strings of multiple cells.
- **Cell Specifications:**
  - NMC/Graphite  
Cylindrical 18650

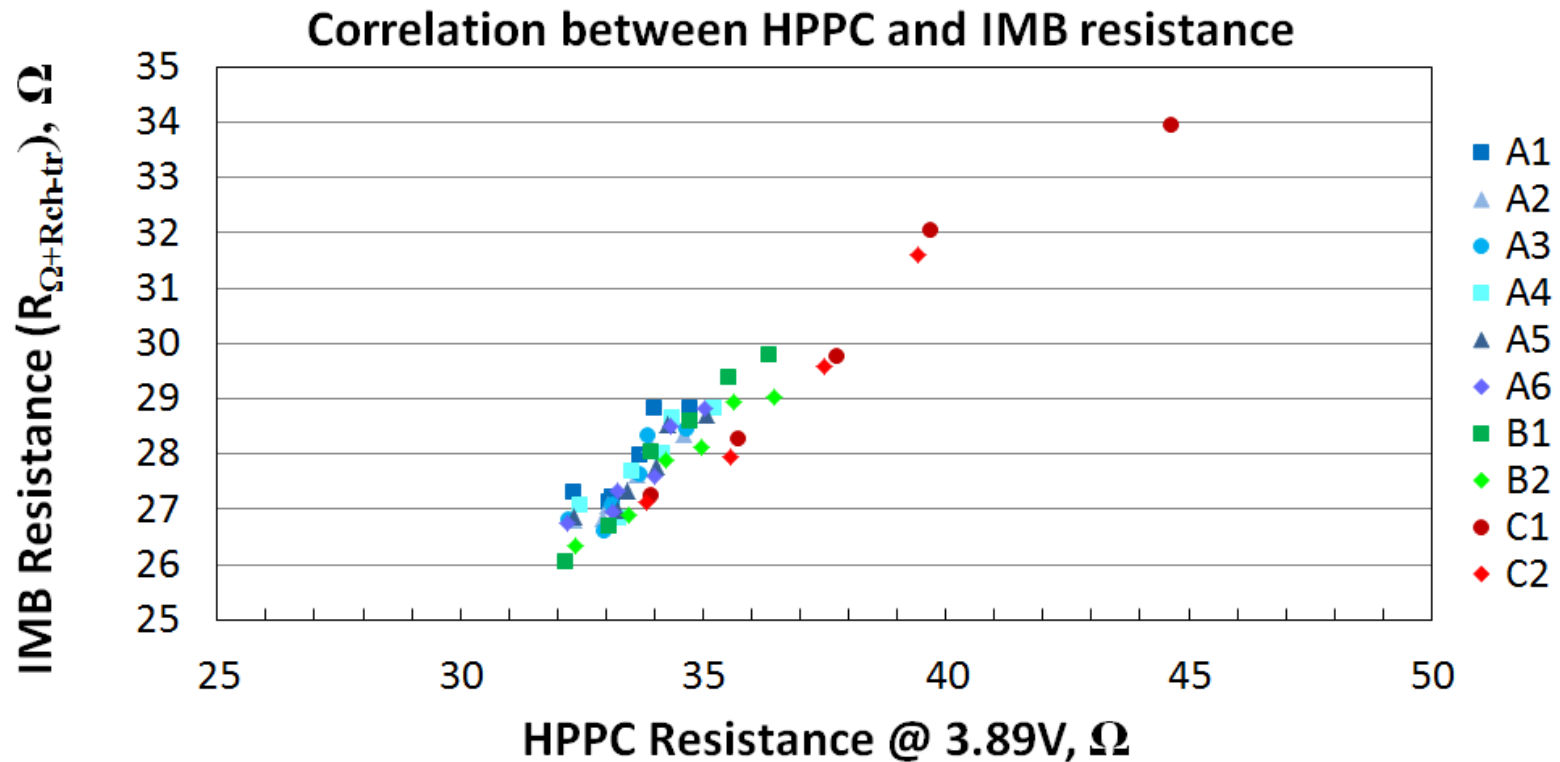
Test Groups @ 60% SOC (3.89V)		
Group	# of Cells	Temperature
A	6	30 °C
B	2	40 °C
C	2	50 °C



***Calendar aging results in modest degradation, making it difficult to detect “faulty” cells. Aging switched to Cycle Life.***

# Progress

## String & Parallel Rapid Impedance (cont.)

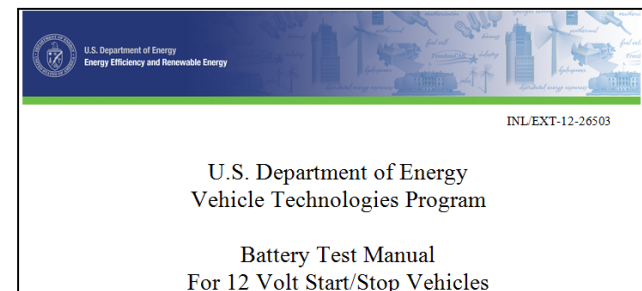
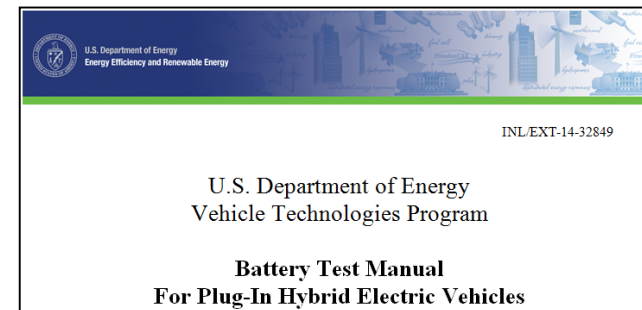
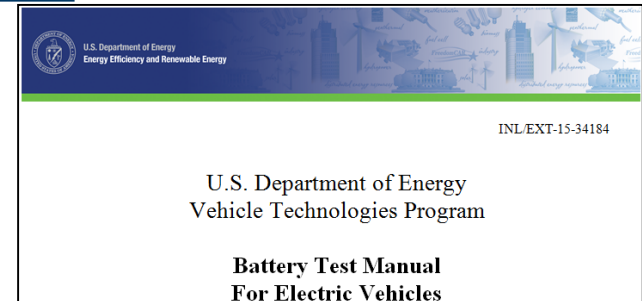


***Good correlation between HPPC discharge resistance and IMB measurements, indicating that acquired data are valid.***



## Test Manuals

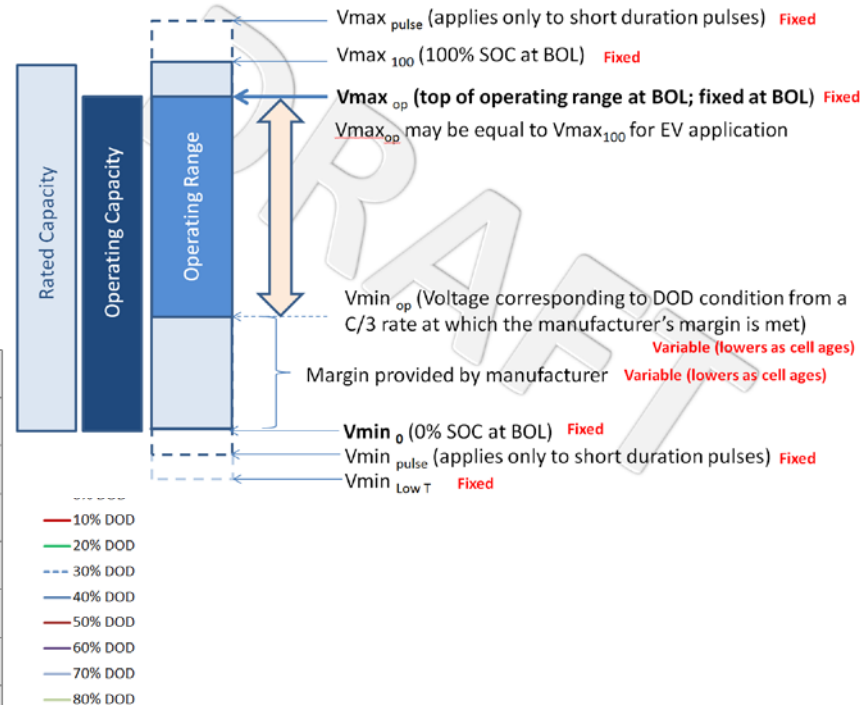
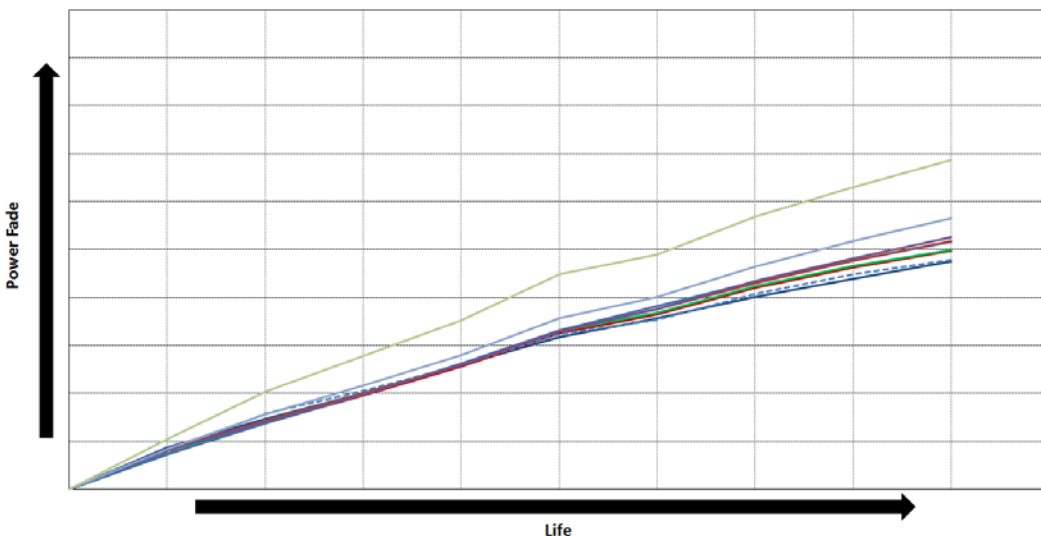
- **Ongoing Revisions (Anticipated Publication):**
  - Battery Test Manual for Electric Vehicles, Revision 3 (June 2015)
    - DRAFT Temporary Manual Released February 2015
  - Battery Test Manual for Plug-in Hybrid Electric Vehicles, Revision 4 (June 2015)
  - Battery Test Manual for 12V Start/Stop Vehicles, Revision 1 (June 2015)
- **Upcoming Publications:**
  - 48-V Manual, Revision 0
- **Noteworthy Item:**
  - Lead National Laboratory for technical content and authorship with support from DOE and USABC.



***Internationally accepted manuals for performance assessment of energy storage systems.***

## Test Manuals: EV Rev. 3

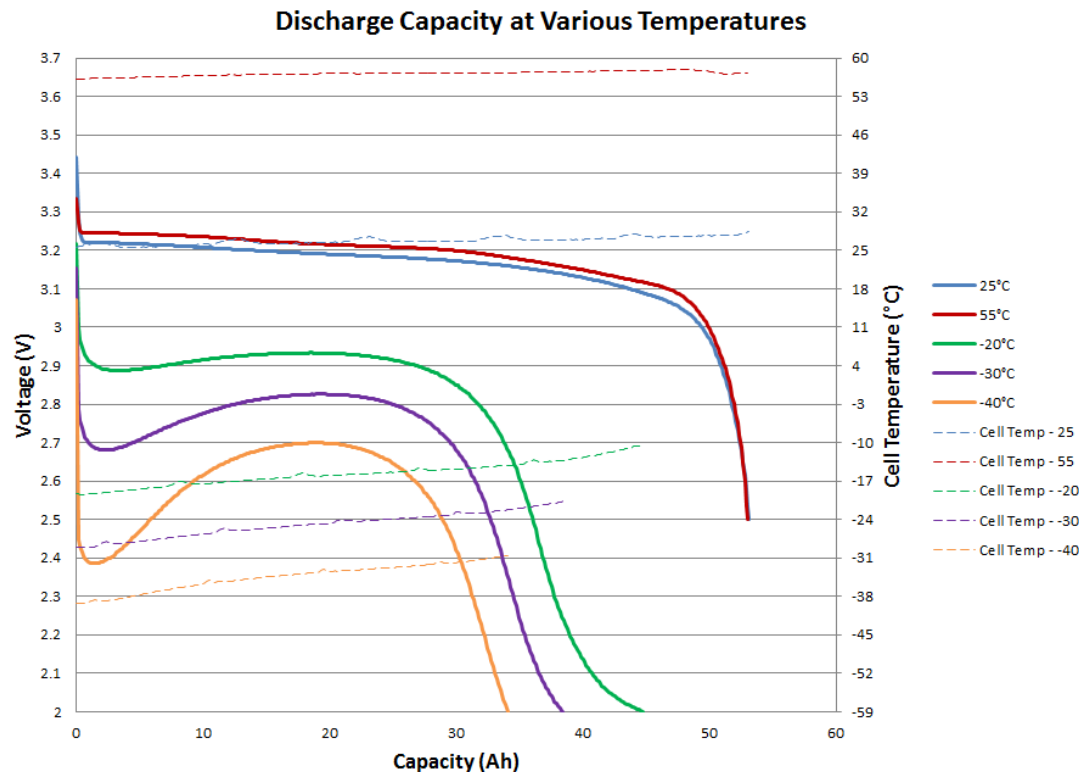
Items considered when drafting the Battery Test Manual for Electric Vehicles, Revision 3



**Pulse Power Capability degradation generally increases at higher DODs, with 80% DOD showing the highest fade.**

## Cold Temperature Performance

- **Purpose:**
  - Characterize the low temperature performance of commercially available cell.
- **Cell Specifications:**
  - Chemistry:  $\text{LiFePO}_4$
  - Rated Capacity: 50 Ah
  - Configuration: Prismatic Aluminum Can
- **Observation:**
  - As the cell temperature rises during discharge, the voltage shows some initial recovery, especially at lower ambient temperatures.



***This cell shows nearly 70% capacity retention at -40°C and nearly 90% capacity retention at -20°C.***

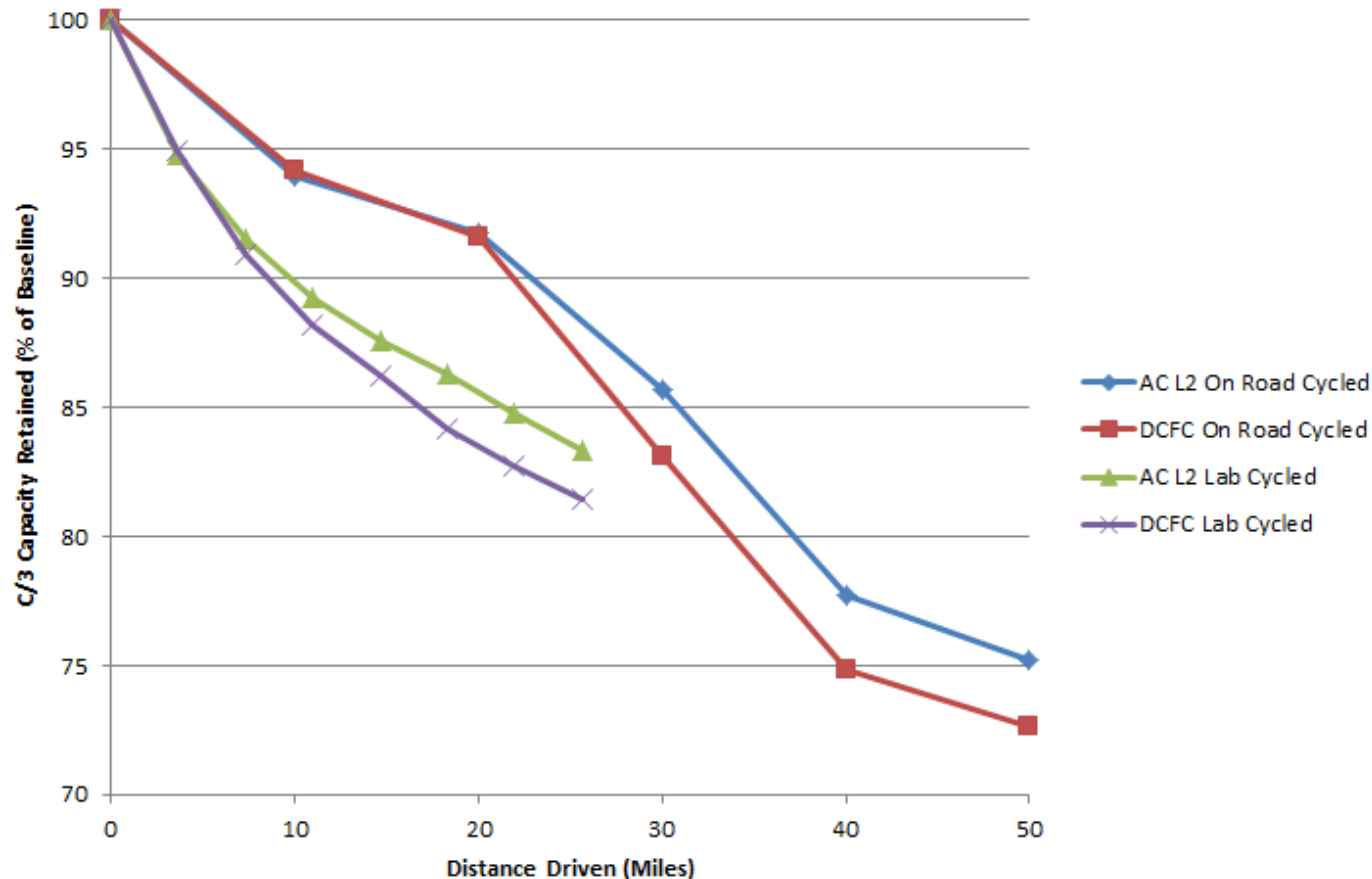
## Performance Science

- **Purpose:**
  - Understanding experiment design through the comparison of on-road and in-lab test results
- **Test Platform:**
  - 2012 Nissan Leaf
- **Test Conditions:**
  - 4 vehicles w/fixed loop drive cycle
    - 2 charging strictly AC Level II
    - 2 charging strictly DC Fast Charge
  - 2 packs @ 30°C using EPA combination highway/city drive cycle
    - 1 charging strictly AC Level II
    - 1 charging strictly DC Fast Charge



***INL Battery Test Center and Advanced Vehicle Testing Activity are working together to address complex problems.***

## Performance Science (cont.)



***Better understanding of lab and on-road results will improve experiment design.***



## ***FY-2014 Deliverables Tested: USABC***

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
LG CPI	Cell	20	6.0	HEV	Ongoing
	Cell	20	15	PHEV 10	Ongoing
	Cell	23	60	PHEV 40	Ongoing
	Pack	2	15	PHEV 10	Ongoing
Maxwell	Cell	15	0.015	LEESS	Complete
	Cell	15	1.1	LEESS	Ongoing
	Cell	1	1.1	LEESS	Complete
	Pack	1	1.1	LEESS	Complete
Envia Systems	Cell	16	22	EV	Complete
	Cell	20 / 1	1 / 20	EV	Complete
Farasis	Cell	20	29	EV	Complete

## ***FY-2014 Deliverables Tested: USABC (cont.)***

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Saft	Cell	12	12.5	HEV	Ongoing
	Cell	5	10	12 V Start/Stop	Complete
	Cell	15	10	12 V Start/Stop	Ongoing
	Cell	12	10	12 V Start/Stop	Ongoing
Quallion	Module	3	52.2	EV	Complete
	Module	3	29	EV	Complete
Leyden	Cell	20	1.7	EV	Ongoing
Entek	Cell	40	2.0	PHEV	Ongoing
K2	Cell	20	51	EV	Complete
	Cell	20	45	EV	Ongoing

***The INL Battery Test Center (BTC) evaluated 294 cells, 6 modules, and 3 packs for USABC in FY-2014.***

## ***FY-2014 Deliverables Tested: DOE Benchmark***

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Axion	Module	12	45	HEV	Ongoing
Hydro-Quebec	Cell	16	1.0	HEV	Ongoing
EIG	Cell	30	5.0	12 V Start/Stop	Ongoing
Lishen	Cell	10	7.5	EV	Complete
Smart Battery	Module	2	40	12 V Start/Stop	Complete
Sanyo	Cell	10	1.2	PHEV	Complete
	Cell	15	1.2	PHEV	Complete
	Cell	20	1.2	PHEV	Ongoing

***The INL Battery Test Center (BTC) evaluated 101 cells and 14 modules for DOE Benchmark in FY-2014.***

# Progress

## ***FY-2014 Deliverables Tested: DOE FOA-2011***

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Miltec (ANL)	Cell	9	0.26	PHEV	Complete
	Cell	9	0.26	PHEV	Complete
Nanosys	Cell	16	1.2	PHEV	Complete
Penn State	Cell	16	3.0	PHEV	Complete
Applied Materials	Cell	16	0.03	PHEV	Complete
Amprius	Cell	16	2.3	PHEV	Complete

***The INL Battery Test Center (BTC) evaluated 82 cells for DOE FOA-2011 in FY-2014.***

## ***FY-2014 Deliverables Tested: DOE FOA-ARRA***

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Exide	Module	3	48	Marine	Complete
EnerG2	Ultra cap	5	100 F	Ucap	Complete
Enerdel	Cell	5	16	PHEV	Complete

**All FOA-ARRA testing has completed and the final report has been delivered to VTO program office**

***The INL Battery Test Center (BTC) evaluated 5 cells, 5 ultra capacitors, and 3 modules for DOE FOA-2011 in FY-2014.***



# Progress

## ***FY-2014 Deliverables Tested: DOE ABR-IC<sup>3</sup>P***

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
ANL	Cell	12	0.25	EV	Ongoing
Envia Systems	Cell	12	0.93	PHEV	Ongoing
Farasis	Cell	12	1.6	EV	Ongoing
Penn State	Cell	12	2.0	EV	Ongoing

***The INL Battery Test Center (BTC) evaluated 48 cells for DOE ABR-IC<sup>3</sup>P in FY-2014.***

## **FY-2014 Deliverables Tested: Summary**

Program	Type	Quantity
USABC	Cell	294
	Module	6
	Pack	3
DOE Benchmark	Cell	101
	Module	14
FOA-2011	Cell	82
FOA-ARRA	Cell	5
	Ultra Cap	5
	Module	3
ABR-IC <sup>3</sup> P	Cell	48

***The INL Battery Test Center (BTC) evaluated 535 cells, 23 modules, and 3 packs for a total of 561 articles in FY-2014.***

# Response to Previous Year Reviewers' Comments

- **Reviewer Comment:**
  - “Several test articles (i.e., cells and packs from the deliverables) were tested in support of the DOE/USABC contracts, but the reviewer criticized that information on these cells/batteries was sadly missing in the presentation. The commenter proposed that it would have been useful to make a proper assessment of this effort and the technology development overall, if these findings (i.e., the test results from these cells and batteries) were published, especially if they are supported by DOE funds.”
- **Battery Test Center (BTC) Response:**
  - USABC testing results are protected information and were therefore not typically shown. Data provided in this poster with permission from developers.
- **Reviewer Comment:**
  - “The reviewer commented that the resources seem to be slightly excessive, although the scope of the project is fairly broad.”
- **Battery Test Center (BTC) Response:**
  - BTC resources are appropriate for a DOE Core Capability facility when considering testing rigor, throughput, and equipment maintenance.

# Response to Previous Year Reviewers' Comments

- Reviewer Comment:
  - “The reviewer indicated that quality testing, validation, and analysis were critical to the successful integration and adaptation of xEV into transportation. The reviewer added that ANLs support of USABC was significant to meet the greater objective. ”
- Battery Test Center (BTC) Response:
  - INL BTC continues to strengthen collaborative ties with other national laboratories (ANL, NREL, SNL) involved in USABC testing. These relationships support the development of higher quality test results and procedures as well as ensure appropriate alignment and overlap to successfully advance and achieve DOE VTO missions.

# Collaboration & Coordination with Other Institutions

- INL and Argonne National Laboratory continue to enjoy a close testing partnership.
  - This collaboration reduces unnecessary duplication and creates valuable overlap of capability where useful.
- INL supplying SNL with aged batteries with known histories for additional abuse testing.
- INL is very involved in several USABC activities and works closely with its partners.
  - Technical Advisory Committee (TAC), as well as the Test Methods & Definitions and Internal Short Circuit Work Groups.
- Expanded test capability will create additional opportunities for collaboration with other national labs (ANL, LBNL, SNL, NREL), industry and academic institutions.
  - Life prediction models, analysis, mechanisms, diagnostics.



# Collaboration & Coordination with Other Institutions

- INL and SNL are collaborating on a joint NHTSA project to define “state-of-stability” assessment tool following an uncontrolled event (e.g., car crash).
  - IMB rapid impedance measurements on individual cells undergoing abusive conditions are being used for a preliminary study.
  - The prototype 50-V system will be used at SNL for module-level abuse studies.
- INL recently loaned a prototype 50-V IMB to the University of Maryland Center for Advanced Life Cycle Engineering (CALCE).
  - The purpose is to develop advanced diagnostic and prognostic modeling tools for industry applications.

# Remaining Challenges and Barriers

- Maintaining a flexible state-of-the-art energy storage device testing facility
  - Adapt to shifting targets and emerging technology
  - Update/modify test protocols and analysis procedures as needed
  - Equipment maintenance, repair, and upgrades
- Expanding lab capability for enhanced data assessment through additional equipment and staffing
- Strengthen and expand collaborative ties with existing Vehicle Technologies Office programs at INL, other national laboratories, and industry.
- Strengthening relationships with suppliers to bolster knowledge on testing needs and requirements (applied pressure, test procedures, etc.).

# Proposed Future Work

- USABC testing deliverables
  - Continue testing existing deliverables
  - Add new deliverables
- Publish updated and new test manuals
  - PHEV Revision 4
  - EV Revision 3
  - 12 V Start/Stop
- Expand lab capabilities
  - Incorporate vibration system where appropriate
  - Additional laboratory support for industry and universities (WFOs, etc.)
  - Develop data management system
- Expand ties with on road and laboratory testing to validate and enhance laboratory modeling capability
- Improve available safety information for first responders

# Summary

- The INL Battery Test Center is the lead DOE laboratory for advanced automotive battery performance testing.
  - 20,000 square feet of lab space with >700 test channels for advanced energy storage testing.
- INL is continuing to support DOE and USABC with science-based performance testing and assessment of candidate battery technologies for various vehicle platform applications.
  - Rigorous NIST traceable calibration procedures for in depth uncertainty analysis.
- INL has strong capabilities in advanced battery diagnostics and prognostics for improved state-of-health assessment.
  - On-going research activities in collaboration with DOE, NHTSA, SNL, and University of Maryland.
- *The INL Battery Test Center (BTC) evaluated 535 cells, 23 modules, and 3 packs for a total of 561 articles in FY-2014*

# Technical Backup Slides

- Battery Tester Specifications and Channel Count

# Equipment

Tester Mfr.	Tester Capability	# of Testers	# of Channels
Maccor	0-5V, +/- 5A	1	8
Maccor	0-5V, +/- 5.5A	3	152
Maccor	0-10V, +/- 12.5A	3	72
Maccor	0-5V, +/- 25A	2	48
Maccor	0-5V, +/- 30A	1	96
Maccor	0-5V, +/- 50A	1	24
Maccor	0-5V, +/- 60A	6	144
Maccor	0-7V, +/- 90A	2	48
Maccor	0-5V, +/- 100A	1	8
Maccor	0-5V, +/- 180A	1	8
Maccor	0-5V, +/- 250A	6	47
Maccor	0-7V, +/- 250A	1	8
Maccor	0-7V, +/- 300A	1	8
PEC	0-50V, +/- 80A	1	8
Maccor	0-55V, +/- 220A	2	8
Maccor	0-65V, +/- 250A	1	4
Maccor	0-60V, +/- 275A	1	4
Bitrode	0-100V, +/- 500A	3	3
Bitrode	0-500V, +/- 350A	3	3
Bitrode	0-1000V, +/- 500A	2	2
Energy Systems	0-500V, +/- 500A	2	2
Total # of Testers/Channels		44	705